The Fourth SM Family Enhancement to the Golden Mode at the Upgraded Tevatron

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Abstract

We study the observability for a Higgs boson at upgraded Tevatron via the modes $gg \rightarrow h \rightarrow ZZ \rightarrow 4l$ ($l = e, \mu$). We find that the signal can be observed at an integrated luminosity of 30 fb^{-1} if the fourth SM family exists.

In the Standard Model (SM) one doublet of scalar fields is assumed, leading to the existence of one neutral scalar particle h. The requirements of the stability of the electroweak vacuum and the perturbative validity of the SM allow to set upper and lower bounds depending on the cutoff scale Λ up to which the SM is assumed to be valid. Experimentally, constraints on the SM Higgs boson are derived directly from the searches at LEP2 which lead to $m_h > 114.3$ GeV [1]. The LHC should be able to cover the full range of theoretical interest up to about 1000 GeV [2]. A Feynman diagram for the Golden Mode of Higgs production and decays through heavy quark triangle loop is shown in Fig. 1.

On the other hand, SM does not predict the number of families of fundamental fermions. In the democratic mass matrix (DMM) approach SM is extended to include a fourth generation of fundamental fermions with masses typically in the range from 300 GeV to 700 GeV [3], [4] (for recent situation see [5]). The fourth SM family quarks will be produced

copiously at the LHC [2]. At the same time a fourth generation of fermions contributes to the loop-mediated processes in Higgs production $(gg \rightarrow h)$ and decays. In this note we consider the influence of the fourth SM family on the Higgs boson search at the upgraded Tevatron.

Two relevant regions of Higgs masses, namely $125 - 165$ GeV and $175 - 300$ GeV, require special attention. For Higgs boson mass above 135 GeV, the decay mode $h \rightarrow WW$ becomes dominant. Hadronic final state is owerwhelmed by the QCD background, therefore, one should deal with $W^\star W^\star \rightarrow l\nu jj$ and $W^\star W^\star \rightarrow l\nu l\nu$ modes [6]. However, the channel $h \rightarrow ZZ$ is also important for the final state observation in the leptonic channel. The decay width for Higgs boson in the channel $h \rightarrow ZZ$ and its branching ratio is given in Fig. 2. In the mass range $135 - 180$ GeV, the width of the Higgs boson grows rapidly with increasing m_h.

For Higgs boson masses in the range $175 < m_h < 300$ GeV, the $h \rightarrow ZZ \rightarrow 4l$ decay mode is the most reliable channel for the discovery of a SM Higgs boson at the upgraded Tevatron if the fourth SM family exists. The discovery potential in this channel is primarily determined by the available integrated luminosity.

The leading production mechanism for a SM Higgs boson at the Tevatron is the gluon-fusion process via heavy quark triangle loop

$$p\overline{p} \rightarrow ggX \rightarrow hX \tag{1}$$

There are also contributions to h production from vector boson fusion processes, which remain at a low level $(2-10)\%$ comparing to the gluon-fusion process. Furthermore, gluon fusion process yields the largest cross section, typically a factor of four above the associated production [6], [7].

The two-loop QCD corrections enhance the gluon fusion cross section by about 80%. Therefore, we simply rescale the three-level cross sections to match the NLO result for the overall rate [8]. The results are shown in Fig. 3. In calculations we have used the CTEQ4M parton distribution functions [9]. In the case of three SM families Higgs boson

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production cross section is roughly 1.0(0.05) pb for $m_h = 100(300)$ GeV. However, this cross section is enhanced by the factor 10(6) due to the fourth family quarks. Obviously, the same enhancement takes place for the Golden Mode and this makes the signal observable over the corresponding background.

In Fig. 4, we present the cross sections for the process $p\bar{p} \to hX \to 4lX$ depending on the Higgs mass for three and four SM family cases. The signal is reconstructed by requiring four charged leptons $4l$ ($l = e, \mu$) in final state. We use the branching ratio $B(Z \to l^+l^-) = 3.35 \times 10^{-2}$ for $l = e, \mu$. In Table I we present the number of "golden" events in the four SM family case at integrated luminosity 30 fb^{-1}.

The most serious background is the pair production of Z bosons, $p\bar{p} \to ZZX(Z \to l^+l^-)$, which has $\sigma \approx 8$ fb and should be taken into account for $m_h > 2m_Z$. This background can be suppressed by consideration of the four-lepton invariant mass distribution. Invariant mass distributions of four charged lepton final state is given in Fig. 5 for two values of Higgs boson mass. We assume the mass window of 10 GeV around the Higgs mass. In the same Figure we present the main background coming from two Z production. In the four SM family case we use $m_4 = 640$ GeV. Taking the mass value $m_4 = 320$ GeV leads to negligible difference in cross sections. As can be seen from the Table II, we obtain 34 signal events against 16 background events within the mass window 10 GeV if $m_h = 200$ GeV. The statistical significance for $4l$ signal is 8.3 and 5.4 for $m_h = 200$ and 250 GeV, respectively.

In conclusion, the Golden Mode will be observable for $175 < m_h < 300$ GeV with more than 3σ significance if the fourth SM family exists. The same statement takes place also for $125 < m_h < 165$ GeV, however we don't consider this region in details because it is covered by $h \to WW$ mode [6], [7].

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TABLE I. The expected number of "golden" events in the four SM family case at integrated luminosity 30 fb^{-1}.

m_h(GeV)	$\Gamma(h \to ZZ)$	$\text{B}(h \to ZZ)$	σ_4(fb)	N(4l)
100	3.9×10^{-3}	6.8×10^{-4}	2.8×10^{-2}	0.8
110	4.6×10^{-3}	2.6×10^{-3}	7.8×10^{-2}	2.3
120	5.6×10^{-3}	9.5×10^{-3}	2.5×10^{-1}	7.5
130	7.4×10^{-3}	2.5×10^{-2}	5.5×10^{-1}	16.5
140	1.1×10^{-2}	4.9×10^{-2}	8.9×10^{-1}	26.7
150	2.0×10^{-2}	6.8×10^{-2}	1.0	30.0
160	8.3×10^{-2}	4.0×10^{-2}	4.9×10^{-1}	14.7
170	3.6×10^{-1}	2.3×10^{-2}	2.4×10^{-1}	7.2
180	6.1×10^{-1}	5.9×10^{-2}	5.0×10^{-1}	15.0
190	9.9×10^{-1}	2.1×10^{-1}	1.4	42.0
200	1.4	2.5×10^{-1}	1.5	45.0
220	2.3	2.8×10^{-1}	1.1	33.0
240	3.4	2.9×10^{-1}	8.4×10^{-1}	25.2
260	4.7	3.0×10^{-1}	6.3×10^{-1}	18.9
280	6.4	3.0×10^{-1}	4.7×10^{-1}	14.1
300	8.4	3.1×10^{-1}	3.6×10^{-1}	10.8

TABLE II. Observability of the "golden" events for integrated luminosity 30 fb^{-1} within the mass window 10 GeV.

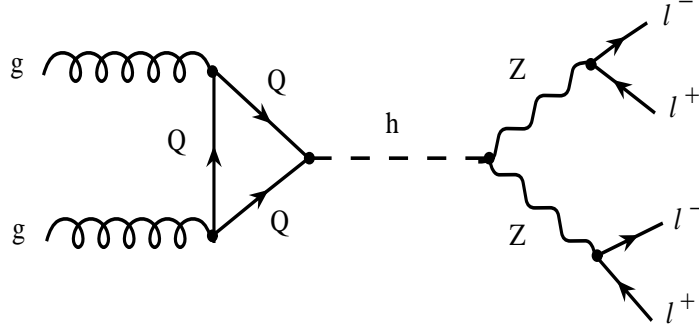|	S		B	S/$\sqrt{\text{B}}$	
m_h(GeV)	SM-3	SM-4		SM-3	SM-4
200	3.5	33.8	16.4	0.9	8.3
250	2.0	16.0	8.8	0.7	5.4

FIG. 1. Feynman diagram for the Golden Mode $gg \to h \to ZZ \to 4l$ at Tevatron.
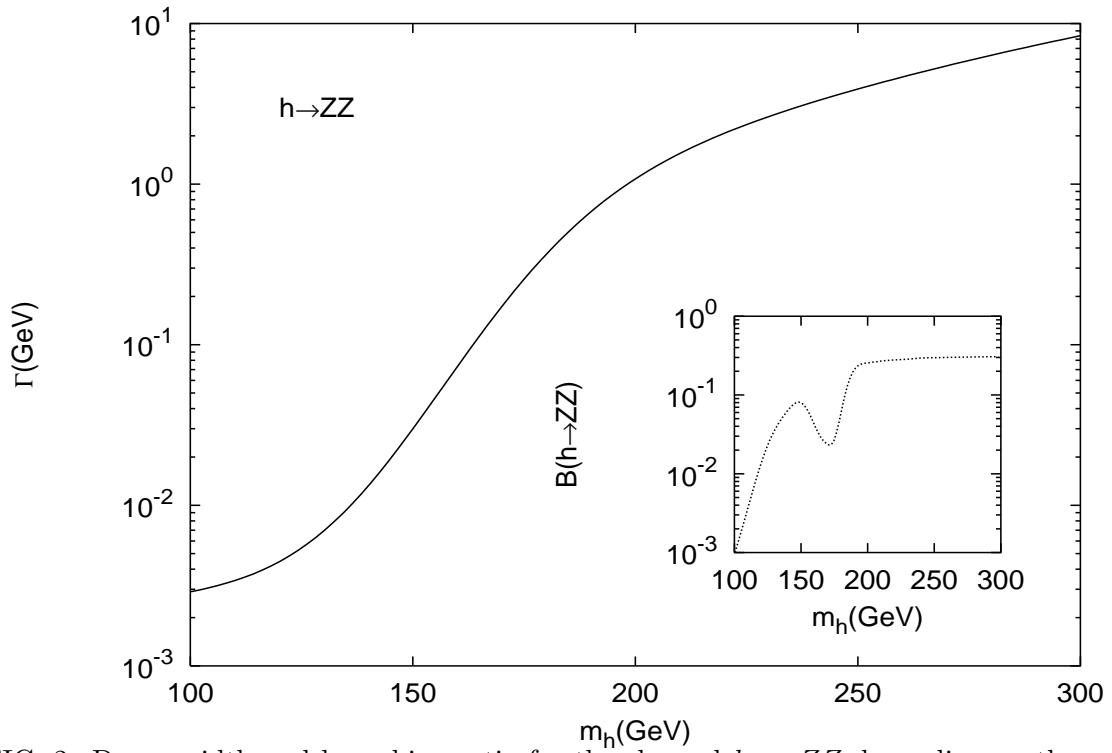
FIG. 2. Decay width and branching ratio for the channel $h \to ZZ$ depending on the mass of
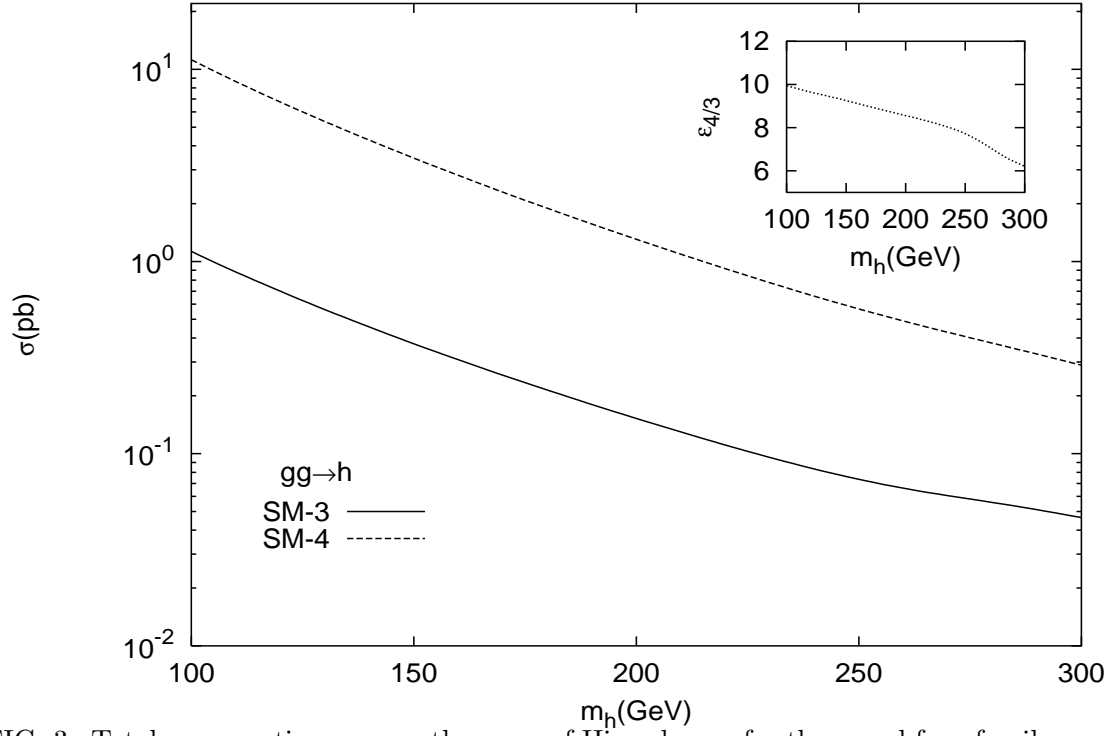
Higgs boson.

FIG. 3. Total cross sections versus the mass of Higgs boson for three and four family cases. An enhancement factor $\varepsilon_{4/3}$ depending on the Higgs mass is also shown.
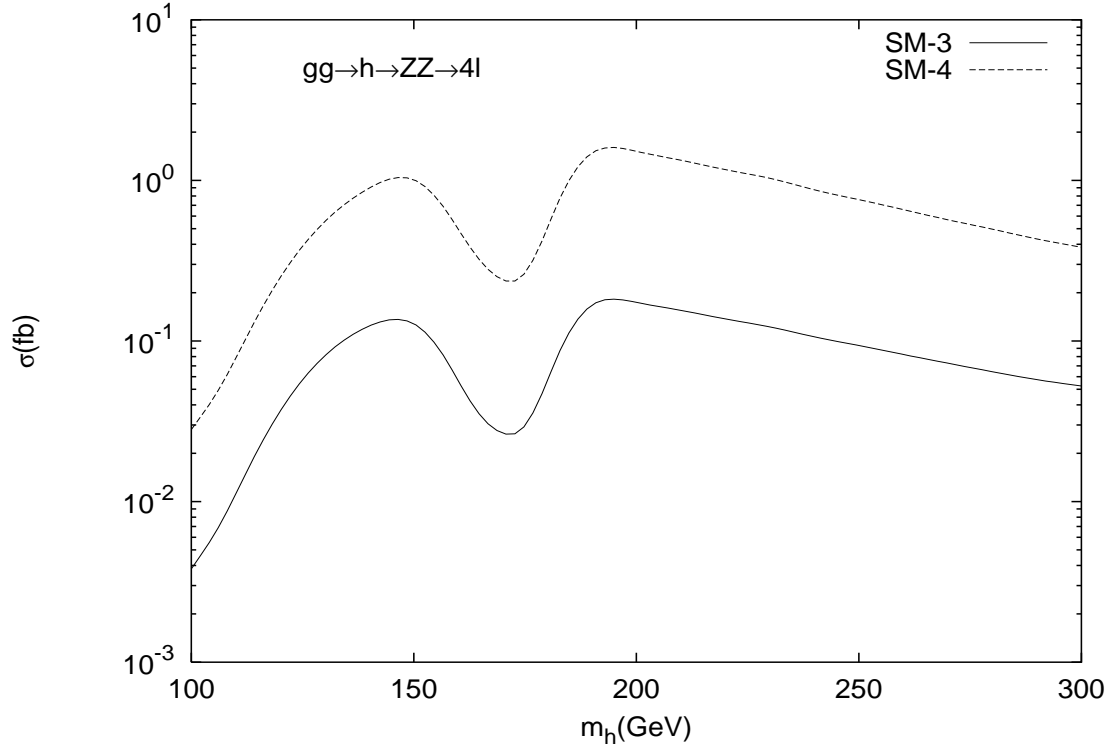
FIG. 4. The cross section of "golden" events depending on the Higgs mass for the cases of three and four SM families.
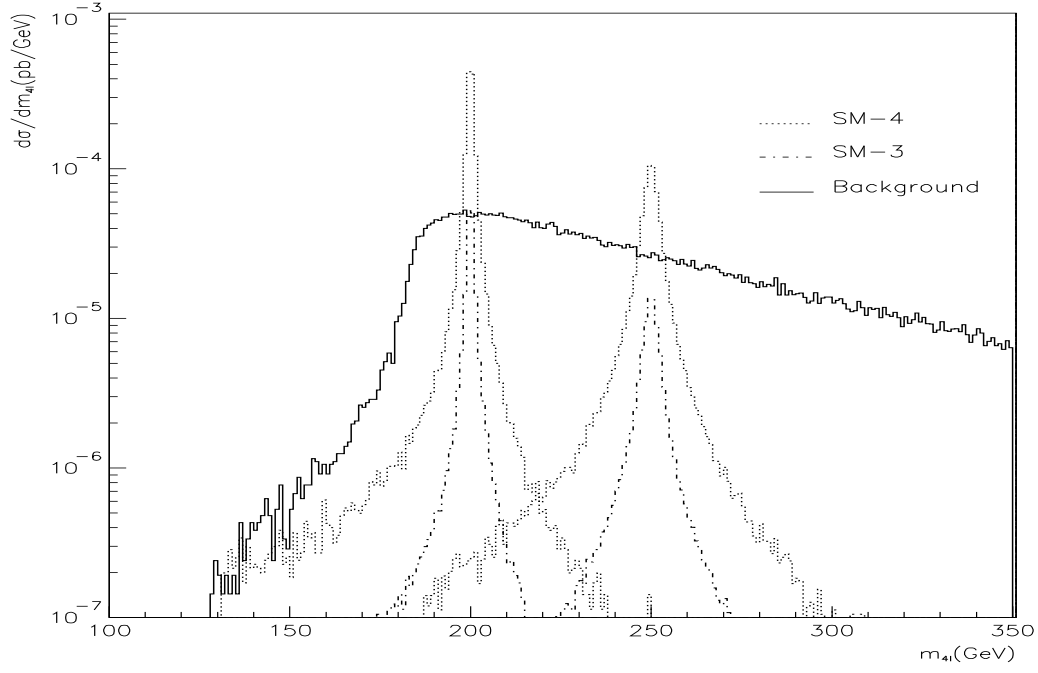

FIG. 5. The invariant mass distributions of the signal and background for $m_h = 200$ and 250 GeV.